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45 degree-TFBG Based High Function Polarisers for In-Fibre Optical Isolator and Coherent Beam Combining for High Power Operation

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14. ABSTRACT

This report results from a contract tasking Aston University as follows: This is a follow-on proposal to our previous project of High extinction ratio in-fibre polarisers by exploiting tilted fibre Bragg grating structures for single-polarisation high-power fibre lasers and amplifiers awarded by EOARD (FA8655-06-1-3068) in September 2006. The scientific findings from this project have given rise to new scope for further R&D on high-function in-fibre polarisation devices in speciality fibres. These new devices may have the potential for implementing novel in-fibre optical isolators and polarisation controllers to be used for coherent beam combining fibre laser and amplifier systems. In order to facilitate the two new AFRL projects - (a) In-fibre optical isolator for high-power operation and (b) Self-organisation for polarisation and coherent beam combination of fibre lasers, proposed respectively by Dr. Gerry Moore and Dr. Tim Newell of AFRL, we propose here to develop high-function in-fibre polarisation devices by exploiting tilted grating structures in high birefringent (hi-bi) and Yb-doped fibres, including both conventional and AFRL project specific types. The specially designed, fabricated and optimised tilted grating devices will be delivered to AFRL for evaluation and finally for integration to their high-power operation in-fibre optical isolator and coherent beam combining systems.

15. SUBJECT TERMS
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Aston/AFRL Project
(EOARD FA8655-08-1-3025)

Final Report

High extinction ratio in-fibre polarisers by exploiting tilted fibre Bragg grating structures for single-polarisation high-power fibre lasers and amplifiers

Nov. 2009

Photonics Research group
Aston University

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Aston/AFRL Project

45°-TFBG based high function polarisers for in-fibre optical isolator and coherent beam combining for high power operation

Report 1

Photosensitivity Evaluation and 45º-TFBG Fabrication in Low-Bi Fibre

13/12/2007

Photonics Research Group
Aston University

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4.2 PDL Measurement using SuperK broadband source

1. Examination of geometry property of AFRL Low-Bi fibre

The geometry properties of the Low-Bi fibre was examined and measured using a high magnification microscope system. The cross-section image of the fibre (Fig.1) shows that:

core diameter: ~10µm;
cladding diameter: ~125µm;
panda eye diameter: ~20µm.

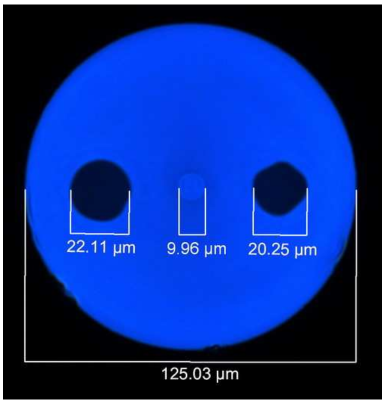


Fig. 1 The cross-sectional image of US LowBi fibre

2. Investigation on photosensitivity of Low-Bi fibre (normal FBG fabrication by UV-inscription)

In order to investigate the photosensitivity of the AFRL supplied Low-Bi fibre, we first carried out the normal FBG fabrication by UV-inscription technique. For comparison, the FBGs were also inscribed in standard telecom fibre under the same UV inscription condition. Prior to the grating fabrication, both Low-Bi and standard telecom fibres were H_2-loaded under the conventional condition (150Pa at 80° for 48 hours) to enhance their photosensitivity. The UV beam was scanned across the fibre with 85mW power at the fibre (~100mW at the laser output) and scanning speed of 0.3mm/s and length 7mm. The FBG spectra were measured after the UV-inscription. For the FBG in Low-Bi fibre the launched light was polarised using a polariser and a polarisation controller. Fig. 2 a & b show the transmission spectra of FBGs UV-inscribed in standard and Low-Bi fibres, respectively. It can be seen clearly that the FBG in Low-Bi is much weaker than that in the standard fibre. The former only achieved ~14dB reflection and the latter achieved ~27dB. The FBG in Low-Bi fibre shows a small polarisation splitting mode effect and the separation between the two polarised modes is about <0.5nm.

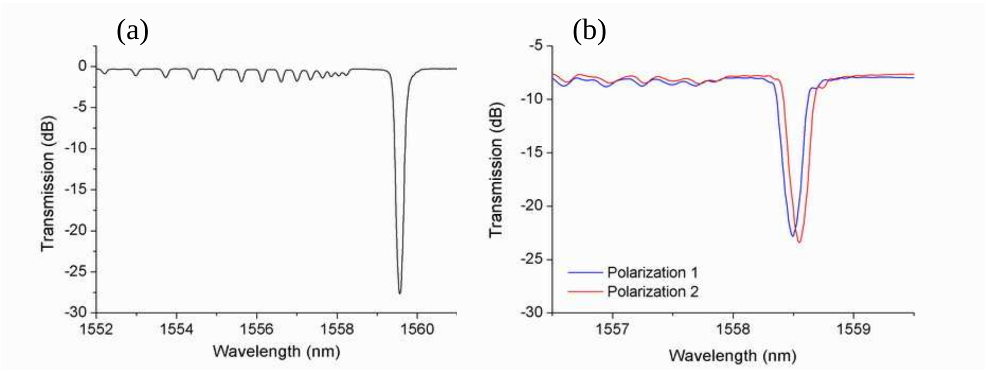


Fig.2 FBG spectra in SMF28 fibre (a) and AFRL Low-Bi fibre (b).

3. 45°-TFBG fabrication

Five 45˚-TFBGs, named as B/Ge-1, B/Ge-2, SMF, LowBi-1 and LowBi-2, have been fabricated in B/Ge, Standard telecom and AFRL supplied Low-Bi fibres. The former two fibres were selected for comparison. As we did not get very consistent results in B/Ge fibre before, this time we decided to use high and low UV power to write 45°-TFBGs in B/Ge fibre. The high power condition was 140mW UV power at the fibre with scanning speed of 0.06mm/s under one scan, and the low power condition was 60mW power at the fibre with the scanning speed at 0.06mm/s under two scans. For the standard and Low-Bi fibres, the UV inscription conditions were the same, as 140mW UV power at the fibre with scanning speed at 0.03mm/s under two scans (Table 1). Because the Low-Bi fibre has two panda eyes, the UV-inscriptions were made along the different fibre orientations. The LowBi-1 was made along the slow axis and the LowBi-2 was along the fast axis of the fibre.

Table 1. Fabrication condition

	B/Ge-1	**B/Ge-2**	**SMF**	**LowBi-1**	**LowBi-2**
Grating Length(mm)	49.2	49	49	49	49
Scan Velocity (mm/s)	0.06	0.06	0.03	0.03	0.03
Multiple Scan (times)	1	2	2	2	2
UV Power at fibre (mW)	140	60	140	140	140

4. PDL characterisation

The PDLs of the five 45°-TFBGs have been measured using two characterisation schemes incorporating a light source, and optical spectrum analyser (OSA), a polariser at 1060nm, a polarisation controller (PC). The first scheme employs a home made 1060nm fibre laser as the light source and the second scheme choose the super continuum light source (Super K®).

4.1 PDL measurement using the home-made 1060nm fibre laser

During this stage, the OSA was set to 0.06nm resolution, and sensitivity was set to -75 dBm. Fig.3 gives the schematic of the PDL measurement system employing the fibre laser. The PDLs of the five 45˚-TFBGs have been measured using this setup and their PDLs are plotted in Fig.4 (a), 5(a) and 6(d), (e), and (f), respectively.

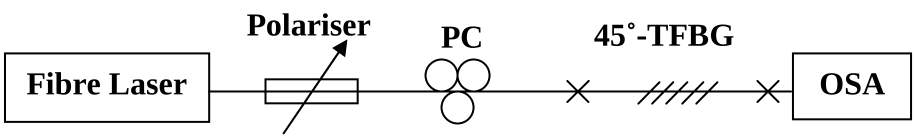


Fig. 3 PDL measurement scheme.

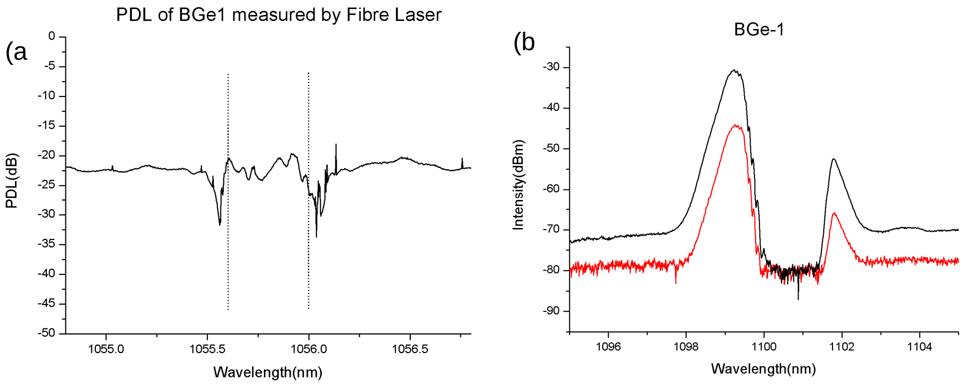


Fig. 4 PDLs of B/Ge-1 measured using (a) home-made 1060nm laser and (b) SuperK at 1100nm.

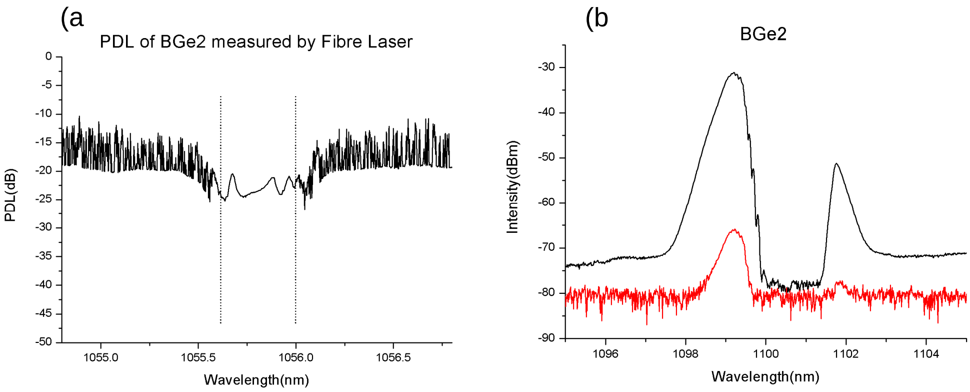
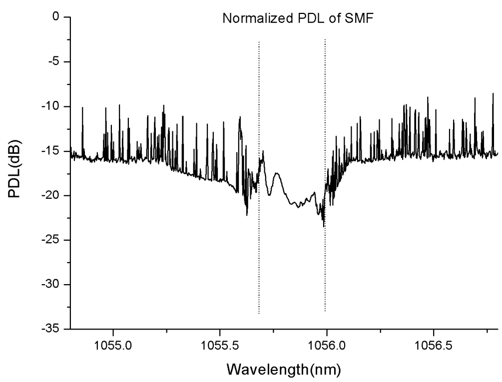
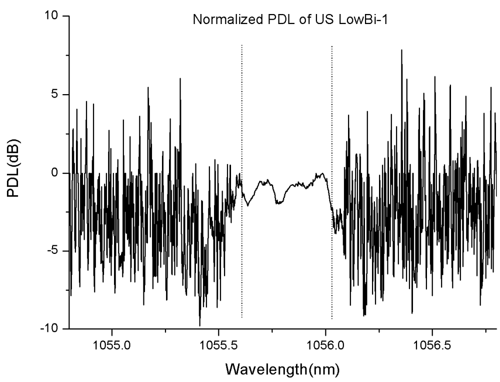


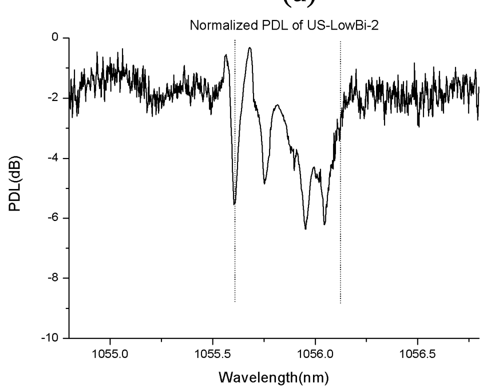
Fig. 5 PDLs of B/Ge-2 measured using (a) home-made 1060nm laser and (b) SuperK at 1100nm.



(a)



(b)



(c)

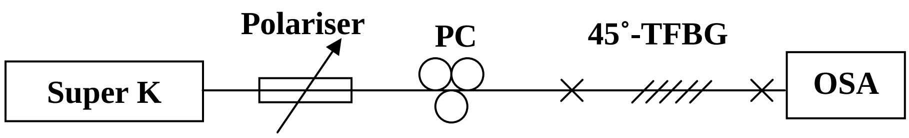
Fig.6 PDLs of 45°-TFBGs measured using home-made 1060nm fibre laser: (a) SMF; (b) LowBi-1 and (c) LowBi-2.

From the fig. 4a and 5a we can see that around 25dB PDLs were achieved by the two B/Ge gratings at 1060nm wavelength. Fig. 6 a, b and c show that at high UV power, 45°-TFBG in standard telecom fibre can achieve ~20dB PDL (this is the first time we have such a high PDL in SMF fibre), but the Low-Bi fibre seems still lack of sufficient photosensitivity and only achieved PDLs around 2-3dB.

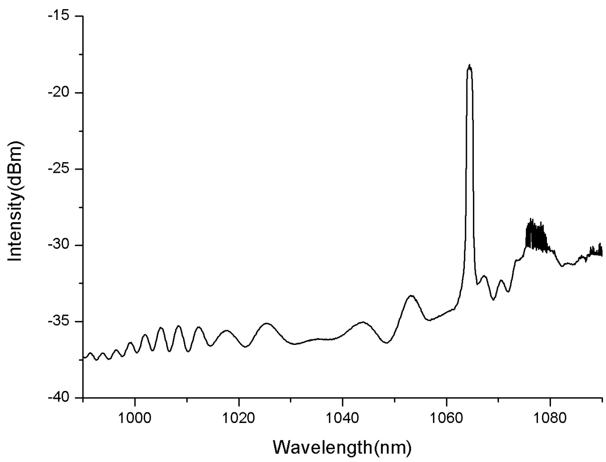
4.2 PDL Measurement using SuperK broadband source

The two B/Ge and the two Low-Bi gratings have also been characterised by super continuum light source (fig. 7a) at around 1100nm region. From the fig. 4b and 5b we see that 35dB PDL was measured for B/Ge-2 grating which was fabricated using lower UV power condition and B/Ge-1 at high power condition only achieved ~25dB PDL. This may not be difficult to explain as the photosensitivity of the B/Ge fibre is outstandingly high after the H2-loading and if the power is too high the UV-induced index modulation could be washed off at the high power, although this needs more experiment to prove.

Fig.7 c and d and e and f depict the normalised and unnormalised PDL profiles for LowBi-1 and 2. For LowBi-1, the PDL is measured from 1040nm to 1140nm and LowBi-2 is measured from 990nm to 1090nm.



(a)



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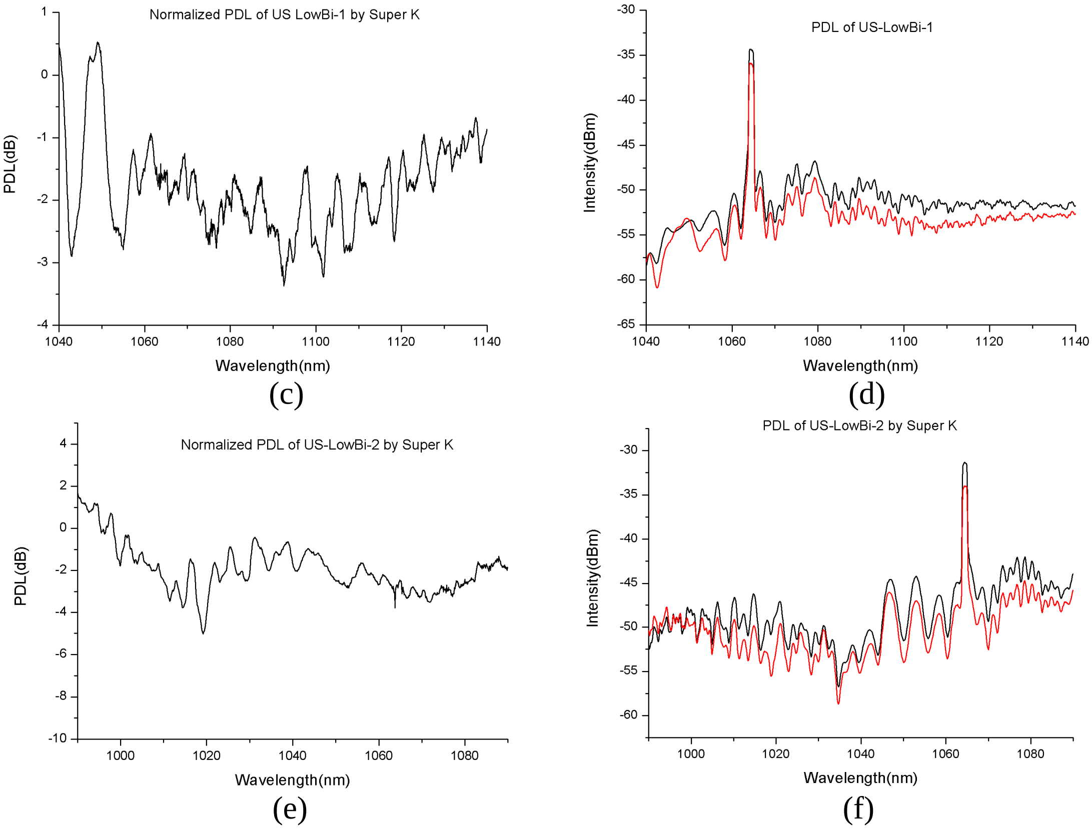

Figure7 (a) Schematic diagram of measurement system; (b) spectrum of Super K from 990nm to 1090nm. Normalised PDLs for (c)LowBi-1 and (e) LowBi-2. PDL spectra for (d) LowBi-1 and (f)LowBi-2.

It can be seen that, the PDLs measured by the superK have a lot of oscillations. Nevertheless, both gratings have not show a high value of PDL, again indicating the photosensitivity of the Low-Bi fibre is not sufficient for 45°-TFBG fabrication. However, this is the first trial and we will further optimise the fabrication condition and repeat the UV-inscription to further confirm the photosensitivity of the Low-Bi fibre in the New Year.

Aston/AFRL Project

45°-TFBG based high function polarisers for in-fibre optical isolator and coherent beam combining for high power operation

Report 2A

Fabrication and characterisation of 45°-TFBGs in standard, photosensitive and polarisation maintaining fibres

14/04/2008

Photonics Research Group
Aston University

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2 Investigation of effects of photosensitivity and UV power on 45°-TFBGs in standard SMF28 and FUD fibres

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3 45°-TFBGs in PM fibre using high UV inscription power

3.1 Specification of the PM fibre
3.2 45º-TFBG fabrication in PM fibre with high UV-power
3.3 PDL of 45º-TFBG in OFS-PM125 fibre

1. Fabrication of four 45°-TFBGs for AFRL project

As requested by the AFRL, we fabricated four 45°-TFBGs in FUD fibre (which was specially purchased photosensitive fibre by AFRL) and delivered them to AFRL in February 2008. Although the FUD fibre has some intrinsic photosensitivity and the host fibre samples were pre-photosensitised using the H_2-loading method (loaded with H_2 at 150bar at 80°C for 48 hours), the grating did not achieve the PDL values as high as that in Aston B/Ge fibre. The maximum PDL is about 23dB which gives a polarisation extinction ratio of 99.5% and this should be sufficient to give single polarisation operation in AFRL prototype isolator system. Further investigation was carried out afterwards to improve PDLs in this special fibre.

The measured PDLs around 1064.45nm for the four delivered gratings are:

FUD_A1: 21.3dB; FUD_A2: 22.6dB; FUD_A3: 17.0dB; FUD_A4: 18.9dB.

Their PDL spectra for two polarisation states are shown in figure 1.

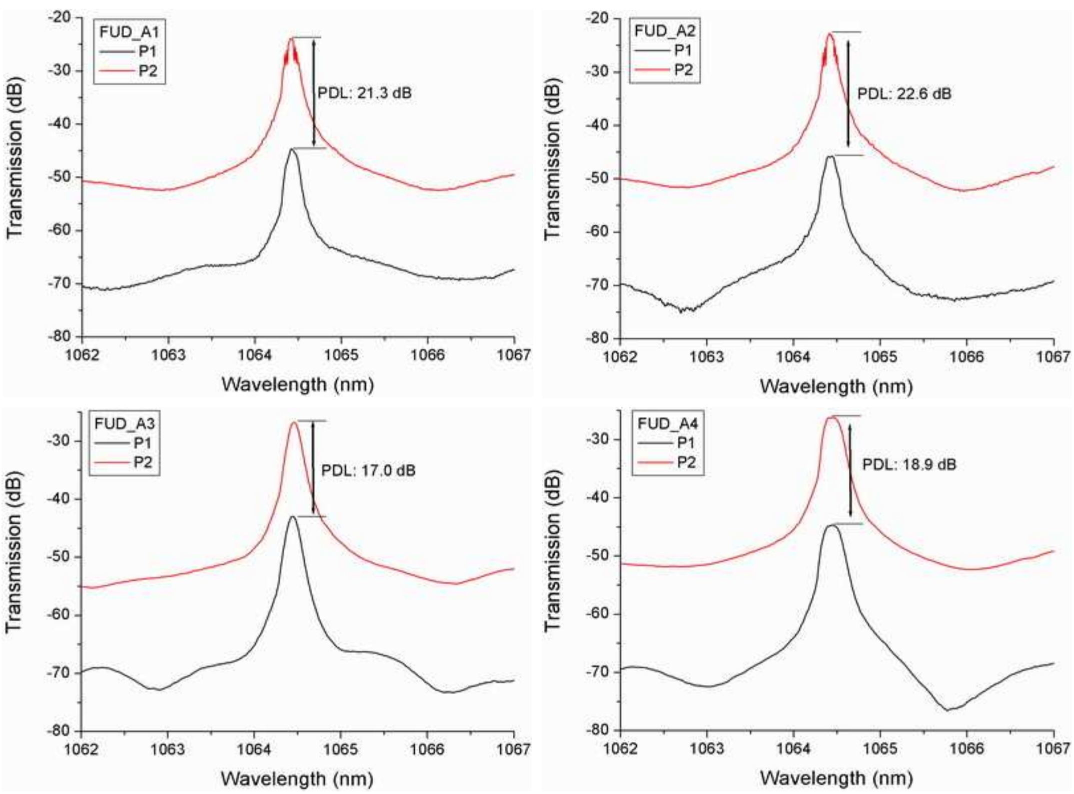


Fig. 1 PDL profiles of 45°-TFBGs in made FUD fibre.

2. **Investigation of effects of photosensitivity and UV power on 45°-TFBGs in standard SMF28 and FUD fibres**

From the fabrication work carried out previously we noticed that the UV power level and fibre photosensitivity are the two major effects on the strength of 45°-TFBGs. With similar UV power used to fabricate 45°-TFBGs in Aston B/Ge fibre, only very weak tilted gratings (PDL less than 2dB) were created in standard SMF28 fibre. We also noticed that the strength of the 45°-TFBGs in B/Ge photosensitive fibre is not necessarily increasing with UV power level, as there may be a saturation effect on absorption. Thus, it is important to investigate the effect of UV power on the strength of 45°-TFBGs in different fibres.

2.1 45°-TFBG fabrication in SMF28 fibre

We investigated the 45°-TFBG fabrication in standard SMF28 fibre using much higher UV power levels - 122mW, 144mW and 166mW - and the same beam scanning condition (the beam was scanned along the fibre twice with a speed of 0.03mm/sec).

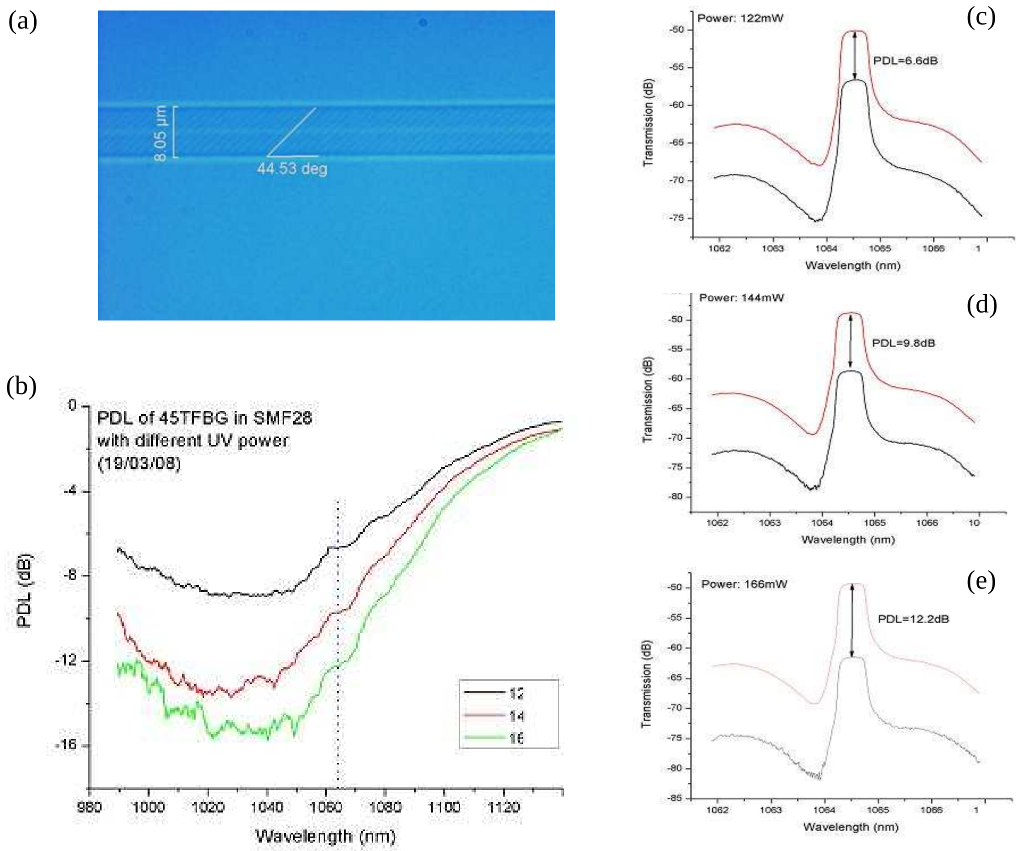


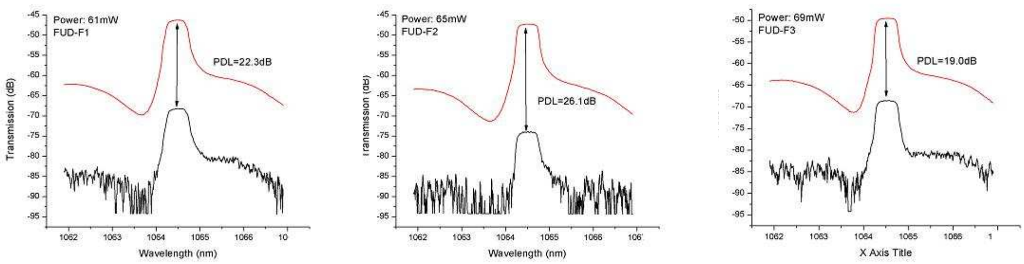
Fig. 2 (a) The image of photoinduced index modulation of the 45°-TFBG UV-inscribed in SMF28 fibre. PDL measurement of 45°-TFBGs in SMF28 fibre with (b) broadband source ranging from 980nm to 1120nm and (c-e) 1060nm single wavelength for three gratings made at different UV power levels.

After the fabrication, the grating fibres were first examined under the microscope and we saw for the first time clear tilted fringes in SMF28 fibre, as shown in figure 2 (a) and then the three gratings were measured for PDLs using our SuperK source, giving the results shown in figure 2 (b-e). It can be seen from the figure that the grating strength in SMF 28 fibre is increasing with UV power level. The PDLs measured are 6.6dB, 9.8dB and 12.2dB at 1060nm (figure 2 c-e) and 9dB, 13.8dB and 15.8dB at ~1030nm (figure 2 b) for the power levels of 122mW, 144mW and 166mW, respectively. The position of the maximum strength seems off the originally designed wavelength 1060nm and is at around 1030nm. This is because the mask was designed using the condition for B/Ge photosensitive fibre not SMF28 fibre. The maximum 16dB PDL (which gives a 97.4% suppression to the s-polarisation) achieved by a 45°-TFBG in SMF28 is encouraging as this could give a solution to low-cost in-fibre polarisers for some applications which require medium polarisation extinction ratio.

2.2 45°-TFBG fabrication in FUD fibre

As we did not achieve 30dB PDL for the 45°-TFBGs delivered to the AFRL, we further investigated the fabrication condition in this fibre. We realised from our previous fabrication in B/Ge fibre that the high power is not necessary to give high grating strength as there may be a saturation effect for UV absorption. We thus used three medium UV power levels to fabricate 45°-TFBGs in FUD fibre.

Three power levels - 61mw, 65mw, 69mw - were selected to investigate UV power effect on grating strength and all other conditions were kept the same as before for the fabrication.



(a) (b) (c)

Fig. 3 PDL at 1064.5nm for 45°-TFBGs in FUD fibre with UV-power levels at 61mw (a), 65mw (b) and 69mw (c).

As shown in figure 3, the achieved PDLs of the three gratings made in H_2-loaded FUD fibre at 1064.5nm are 22.3dB, 26.1dB, and 19.0dB for the three power levels, respectively. The highest PDL of 26.1dB is obtained for 65mW UV power, but it is still lower than a typical value of 30dB of 45°-TFBGs in B/Ge fibre. This indicates again that the intrinsic photosensitivity of FUD fibre is not as high as that of Aston

B/Ge fibre. However, there may be some less trivial factors which also affect the strength of the gratings in FUD fibre and further investigation is needed to identify them.

3 45°-TFBGs in PM fibre using high UV inscription power

In the first stage of AFRL/Aston project, Aston had investigated the fabrication of 45°-TFBGs in AFRL supplied PM fibre with some photosensitivity. The tilted grating structures were created in this PM fibre but with relatively weak strength. At that time, the gratings were fabricated with low UV power as the laser tube was near its end of lifetime. Since now 45°-TFBGs with PDL up to 16dB can be produced in standard SMF28 fibre using high UV power, it is necessary to see if 45°-TFBGs with relatively high strength can also be produced in PM fibre using higher UV power.

3.1 Specifications of the PM fibre

The PM fibre was made by OFS doped with some Ge and we named it as OFS-PM125. The microscope image confirms the geometry of the fibre as Core/Cladding/Panda diameters: 8μm/125μm/36μm.

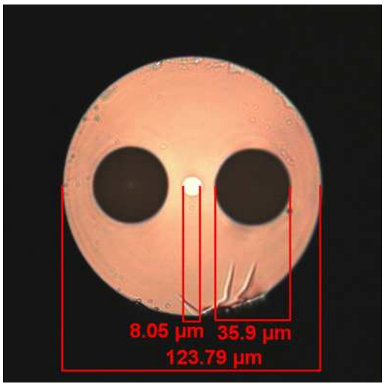


Fig. 4 Cross-section image of the PM fibre.

3.2 45°-TFBG fabrication in PM fibre with high UV-power

In order to maximise the UV absorption, the OFS-PM125 fibre was H_2-loaded under 150bar at 80° for 48 hours prior to the UV-inscription. The UV power focused on the fibre core was at 144mW which is higher than 105mW used before. The scanning speed was kept at 0.03mm/s and the UV beam was scanned twice along the fibre.

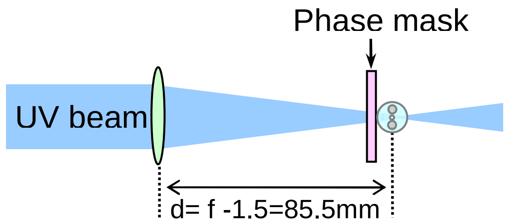


Fig.5 *The 45°-TFBG fabrication system using phase mask method with the fast-axis orientation.*

Similar to the before, the fibre was marked with its axis and the UV beam was incident to the fast-axis of the PM fibre for grating inscription, as shown in figure 5.

3.3 PDL of 45°-TFBG in OFS-PM125 fibre

The SuperK source was employed to measure the PDL of the 45°-TFBG made in the PM fibre. Figure 6 shows the PDL measurement system employing the SuperK source, polariser, polarisation controller and an optical spectrum analyser (OSA).

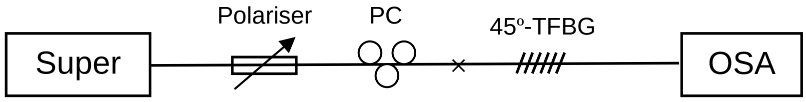


Fig.6 Schematic diagram of PDL measurement of 45°-TFBG.

In the experiment by controlling the polarisation controller, the maximum and minimum output profiles were obtained on the OSA. The difference between these two traces gives the PDL of the grating.

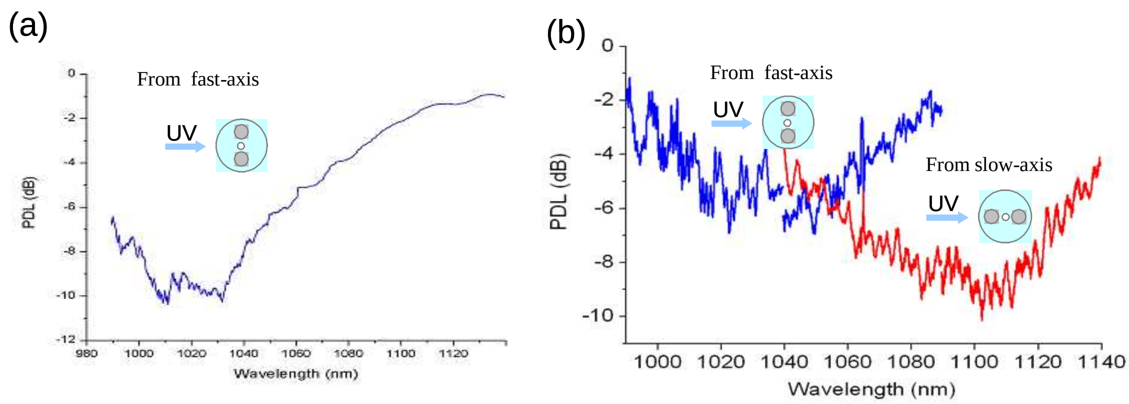


Fig. 7 (a) PDL of 45°-TFBG in OFS-PM125 fibre UV-inscribed from fast-axis orientation. (b) PDLs of previously made 45°-TFBGs UV-inscribed from different orientations: (a) slow-, (b) fast-axis.

Figure 7 (a) shows the PDL over the wavelength range from 980nm to 1120nm of the 45°-TFBG UV-inscribed to the PM fibre from its fast-axis direction. It can be seen

that the maximum PDL is about10.5dB at around 1020nm. This value is higher than 7dB of the grating made previously in the same PM fibre (figure 7 b). This proves that high PDL may be achievable in the PM fibre using high UV power and the PDL may be further increased by using even higher power. More work will be carried out in near future to enhance the quality of the 45°-TFBGs in PM fibres.

Aston/AFRL/Liekki project

45°-TFBG based high function polarisers for in-fibre optical isolator and coherent beam combining for high power operation

Report 2B

Theoretical and experimental investigation on coupling between 45˚-TFBG and polarisation maintaining (PM) fibre

14/04/2008

Photonics Research Group
Aston University

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3. **Experimental Investigation and Discussion**

   3.1 Characteristics of 45˚-TFBG

   3.2 Coupling experiment

4. **Conclusion**

1. **Introduction**

45°-TFBGs behaving as an in-fibre polariser have been demonstrated recently [1]. Inscription of 45°-TFBGs in single-mode fibre gives intrinsic advantages such as low insertion loss, high compatibility with conventional fibre systems, etc. However, the coupling between single mode 45°-TFBG and specialty fibres is important to investigate for optimisation of the all-fibre systems utilising 45°-TFBGs. This report gives the outcome of theoretical and experimental investigation on coupling between 45°-TFBG and polarisation maintaining (PM) fibres.

2. **Theoretical Modelling**

Because 45˚-TFBG behaves like an in-fibre polariser, the light pass through it can be regarded as linear polarised light. The polarisation state of the light after propagating through the PM fibre may be identified using Jones Matrix. A schematic system configuration involving the coupling between a 45°-TFBG and a PM fibre is shown as below.

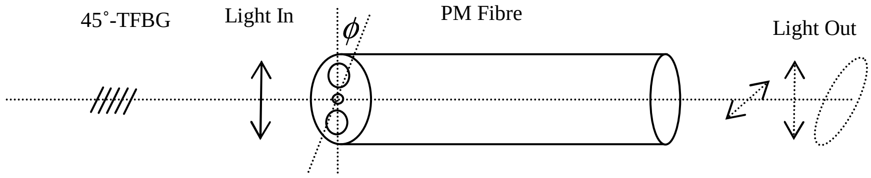


Figure.1 Schematic diagram of state of polarisation measurement within 45˚-TFBG and PM fibre coupling system.

Assuming that the retardation of the PM fibre is θ, we can express the transfer matrix T_r by using Jones Matrix as following:

$$T_r = D(\theta)R(\phi) \qquad (1)$$

where $D(\theta)$ and $R(\phi)$ indicate the Jones Matrix of retardation and the coordinate rotation, and are given as below:

$$D(\theta) = \begin{bmatrix} e^{-\frac{i\theta}{2}} & 0 \\ 0 & e^{\frac{i\theta}{2}} \end{bmatrix}, \quad R(\phi) = \begin{bmatrix} \cos\phi & \sin\phi \\ -\sin\phi & \cos\phi \end{bmatrix} \qquad (2)$$

The state of polarisation of the output light can be easily calculated by the following expression:

$$L_{out} = T_r L_{in} = \begin{bmatrix} e^{-\frac{i}{2}\theta} \cdot \sin\phi \\ e^{\frac{i}{2}\theta} \cdot \cos\phi \end{bmatrix} \qquad (3)$$

where L_{in} is the Jones Vector of the incident light, expressed as :

$$L_{in} = \begin{bmatrix} 0 \\ 1 \end{bmatrix} \qquad (4)$$

L_{in} is assumed to be vertically linear polarised light.

If $\phi = 0$ which means there is no misalignment, then the state of polarisation (SOP) of output light L_{out} should be

$$L_{out} = \begin{bmatrix} 0 \\ e^{\frac{i}{2}\theta} \end{bmatrix} = e^{\frac{i}{2}\theta} \begin{bmatrix} 0 \\ 1 \end{bmatrix} \qquad (5)$$

Expression (5) means the output light is also a vertically linear polarised light, the same as the incident light. Also the change of retardation of the PM fibre does not change the polarisation state, which means environmental fluctuation does not change SOP of the output light.

If $\phi = \frac{\pi}{2}$, which means the incident light propagates along the slow axis of the PM fibre. Then the SOP of output light is shown below:

$$L_{out} = \begin{bmatrix} e^{-\frac{i}{2}\theta} \\ 0 \end{bmatrix} = e^{-\frac{i}{2}\theta} \begin{bmatrix} 1 \\ 0 \end{bmatrix} \qquad (6)$$

Expression (6) means the output light becomes a horizontally linear polarised light.

For other cases, i.e. $0 < \phi < \frac{\pi}{2}$, the SOP of the output light can be shown as expression (3). It can be obviously seen that the output light is elliptical polarised. Also, the SOP of the output light is not stable, which is very easily affected by environmental fluctuation such as temperature change or vibration of the PM fibre.

3. Experimental investigation and discussion

3.1 Characteristics of 45˚-TFBG

The 45˚-TFBGs were UV-inscribed in hydrogen loaded standard fibres (Corning SMF-28) using scanning phase mask technique with a 244nm UV source from a CW frequency doubled Ar+ ion laser. A phase mask with a period of 1800nm was rotated 33.7˚ with respect to the fibre axis to produce titled fringes of 45˚ in the fibre and induce radiation response around 1550nm range. Limited by the size of the phase mask, the maximal length of the 45˚-TFBG is only about 3.8mm. So long length gratings can only be fabricated by concatenation. In our experiment, 13 sections of short grating have been concatenated, giving a final 45°-TFBG with 49.4mm length. Its polarisation dependent loss (PDL) was tested by using EXFO DWDM Test System

which scans the PDL within 100nm range via an internal tuneable laser. The PDL spectrum of this 45-TFBG is shown in figure 2.

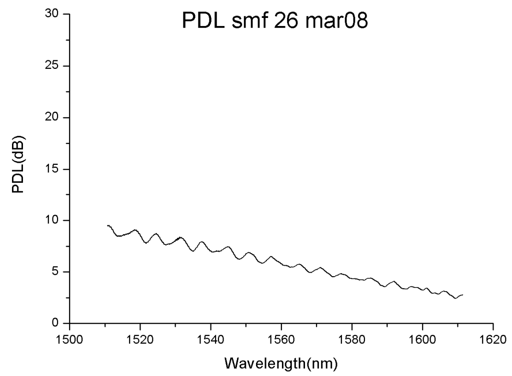


Figure.2. PDL of SMF concatenation 45˚-TFBG by tunable laser scanning

Because it is made in non-photosensitive standard fibre and using the concatenation method, the PDL is much lower than that in B/Ge fibre. From the figure we can see that the PDL is ~10dB around 1550nm.

3.2 Coupling experiment

The investigation for 45˚-TFBG and PM fibre coupling system incorporates a single wavelength light source (EXFO FLS-2100), polarisation controller (PC), 45˚-TFBG, a piece of PM fibre and a polarimeter (Thorlabs PAT9000B). The schematic configuration is shown below in figure 3.

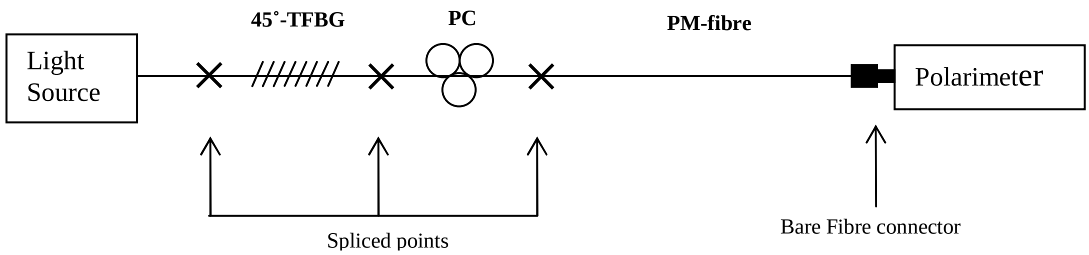


Figure.3.Experimental setup for coupling between 45˚-TFBG and PM fibre

The PAT9000B polarimeter can perform a number of measurements including degree of polarisation (DOP), ellipticity, azimuthal degree, also can show the state of polarisation (SOP). Because the PM fibre can not be rotated in this system, it was not possible to set the fast and slow axis by rotation. Due to the polarisation mode dispersion of the PM fibre, if we change the polarisation state of the incident light to the PM fibre we shall see linearly or elliptically polarised state in the Polatimeter. To examine the coupling effect, a polarisation controller is inserted between the 45°-TFBG and the PM fibre to control the alignment of the linearly polarised light from the 45°-TFBG and the fibre axis of the PM fibre. With the polarimeter, we can find out the two principal axes by locating the highest DOP. We then examined the coupling and system stability for three cases – linearly polarised light out from the 45°-TFBG aligning with the fibre slow- and fast-axis and between the two axes. Note, because the output side of pigtail of the 45°-TFBG is very short, we can assume that

the light from the 45°-TFBG is maintaining linear polarisation. Figure 4 shows the cross section of the PM fibre we used in this experiment. In order to eliminate insertion loss and instability, all fibres in this system were fusion spliced for connection.

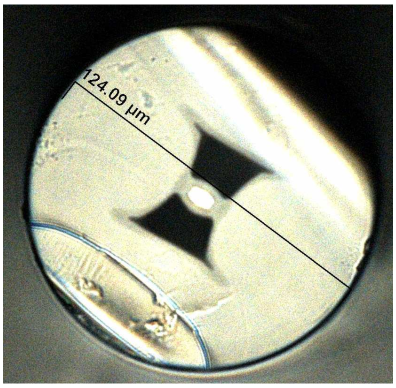
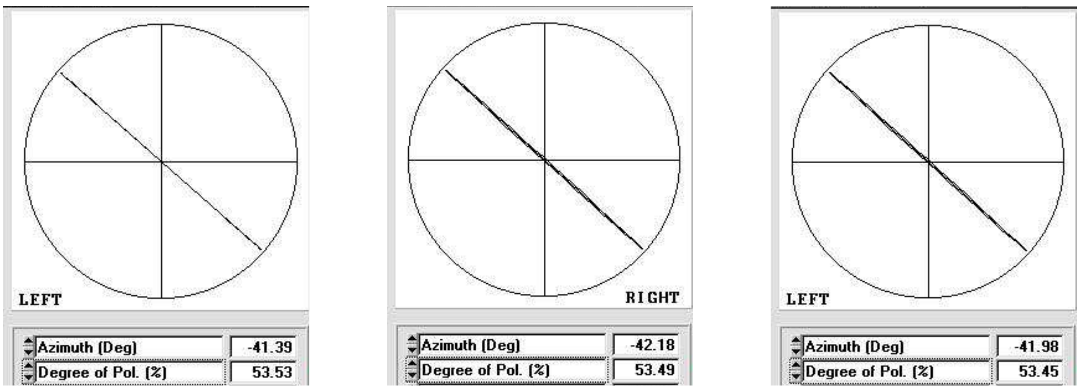


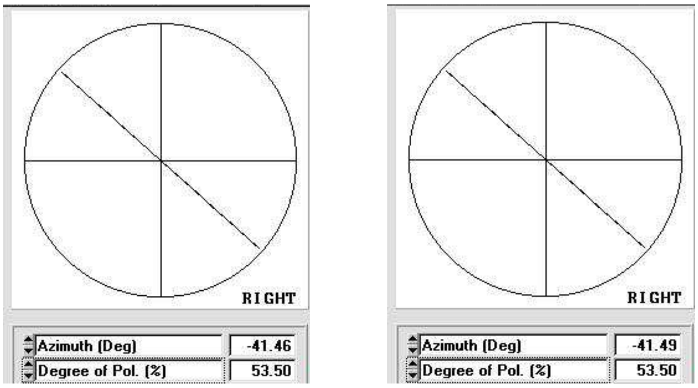
Figure.4. cross section image of the bow-tie PM fibre under microscope

The light source used in the system is the EXFO tunable laser of single mode operation and we used a single wavelength at 1539nm. The single mode operation was checked by an external photo-detector (PD) and electronic spectrum analyser (ESA). There was no beat frequency observed. The single mode operation ensures high DOP measurement.

By carefully adjusting the PC, we can get the highest DOP at one particular direction in terms of azimuthal angle. As shown in figure.5 (a) and figure.6 (a), we can align the linearly polarised light to the slow- and fast-axis of the PM fibre, giving the highest DOP showing on the Polarimeter. From the azimuthal angle reading on the figures, we see the two polarised states are orthogonal, 90° (42° + 48° = 90°), to each other, proving they are along the slow- and fast-axis. In these two situations, the polarisation state can be maintained in a PM fibre. This was proved by examining the stability of the polarisation state when the PM fibre was subjected to arbitrary bending (manually bent the PM fibre) and vibration (knocking the PM fibre at different location). As clearly shown in figure 5 (b-e) and 6 (b-e), the polarisation states were stable under these external perturbations. From the azimuthal angle readings shown in the figures, we can see they almost maintain at a constant value, indicating good polarisation stability.

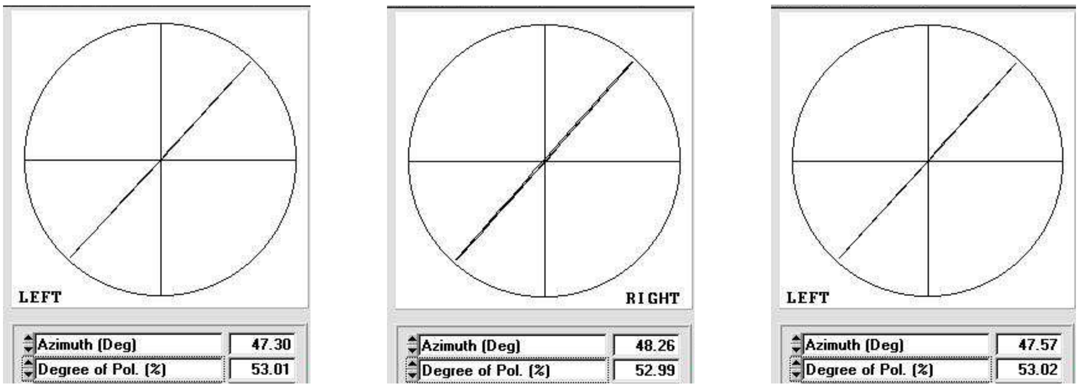


(a) fast axis (b)bending 1 (c) bending 2

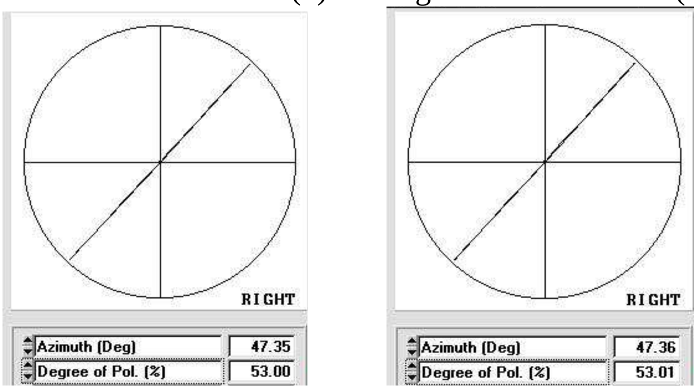


(d)vibration 1 (e)vibration 2

Figure.5. polarisation state for fast axis: (a) no perturbation; (b) & (c) PM fibre under arbitrary bending; (d) & (e)Pm fibre under arbitrary vibration



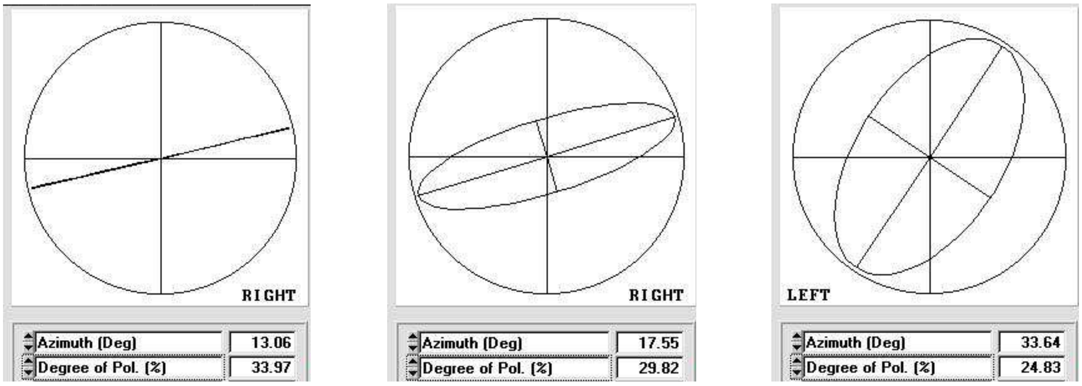
(a)slow axis (b)bending 1 (c)bending 2



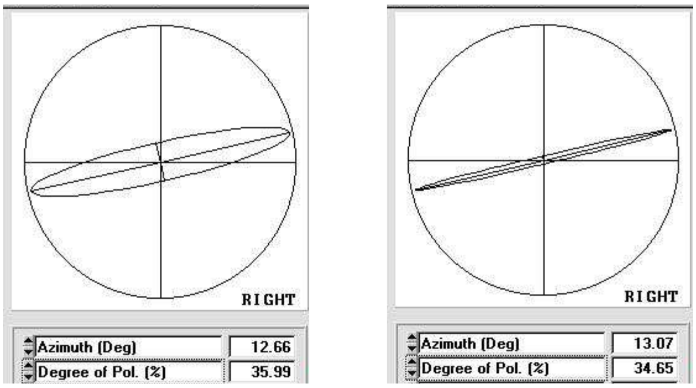
(d)vibration 1 (e)vibration 2

Figure.6. polarisation state for slow axis: (a) no external perturbation; (b) & (c) under arbitrary bending; (d) & (e) under arbitrary vibration.

We then performed the experiment by aligning the linearly polarised light to an arbitrary angle to the fast- (or slow-) axis and examine the polarisation state and its stability of the output light from the PM fibre. Figure 7 (a) shows the output light from the PM fibre is linearly polarised, but not aligned with either fast- or slow-axis. In this case, the PM fibre does not resist the external perturbation. As clearly shown in figure 7 (b-e), when the PM fibre is under bending or vibration the output light is no long linearly polarised; it changes to elliptical polarisation state, thus lost the polarisation maintaining function. From the figures we also noticed that for some situations, the azimuthal degree changes.

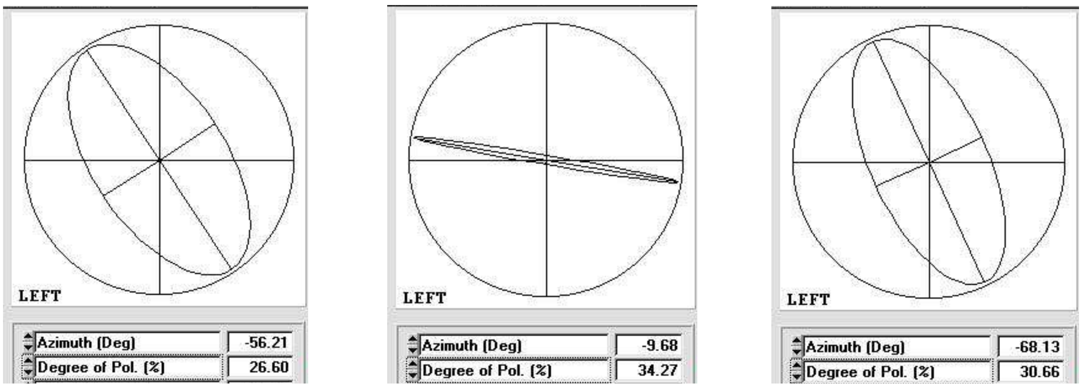


(a)linear polarised (b) bending 1 (c) bending 2

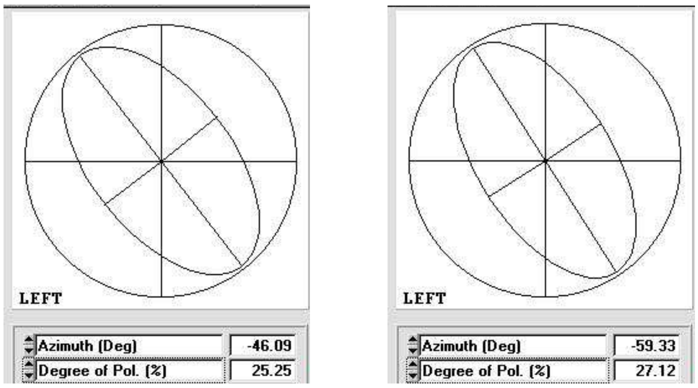


(d)vibration 1 (e)vibration 2

Figure.7. Arbitrary linear polarisation state: (a) no perturbation; (b) & (c)under bending; (d) & (e) under vibration.



(a)elliptical polarised (b)bending 1 (c)bending 2



(d)vibration 1 (e)vibration 2

Figure.8. Arbitrary elliptical polarisation state: (a) no external perturbation; (b) & (c)under bending; (d) & (e)under vibration.

We then change the PC to select an arbitrary elliptical polarisation state as shown in figure 8 (a) and applied bending and vibration to the PM fibre. As shown from figure 8 (b-e), the DOP degrades and azimuth angle changes significantly, indicating arbitrary polarisation state of the light from the PM fibre.

4. **Conclusion**

We have theoretically and experimentally investigated the coupling between 45˚-TFBG and a PM fibre. The results show that the alignment between 45°-TFBG and the PM fibre is vitally critical. Only the linearly polarised light from the 45°-TFBG is coupled in a PM fibre along its fast- or slow-axis, the output from the PM fibre will maintain linear polarisation state and also resist external perturbation, otherwise, the output light from the system will no long linearly polarised and the polarisation state is easily influenced by external perturbation.

Aston/AFRL project

45°-TFBG based high function polarisers for in-fibre optical isolator and coherent beam combining for high power operation

Report 3A

Dual-wavelength switchable single polarisation erbium-doped fibre laser using 45° - and 77° -TFGs

7/11/2008

Photonics Research group
Aston University

Contents

1. **Introduction**
2. **Fabrication and Characterisation of Gratings**
   2.1. Seeding Fibre Bragg Gratings
   2.2. The property of the 45°-TFG
   2.3. The property of the 77°-TFG
3. **Experimental Setup of the Proposed Fibre Laser and Results**
4. **Conclusion**

1. **Introduction**

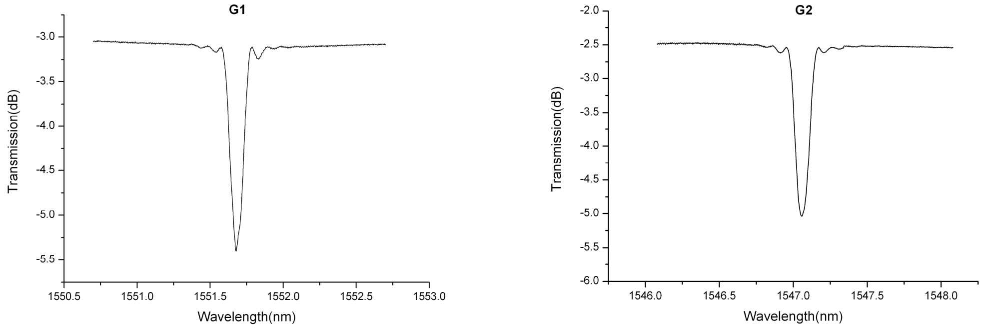
Optical fibre lasers of switchable multi-wavelength output are useful light sources for applications in wavelength division multiplexed (WDM) optical fibre communication systems, fibre sensors, and optical instrument and system diagnostics. Fibre Bragg gratings (FBGs) are ideal wavelength selective optical components for fibre lasers due to their advantages such as intrinsic fibre compatibility, ease of use, and low cost etc. Erbium-doped fibre (EDF) has been developed and widely used for commercial fibre lasers and amplifiers owing to its high optical gain in 1550nm region. Because of its relatively broad homogeneous excitation, it is difficult to obtain stable and simultaneous wavelength oscillations in EDF lasers (EDFLs). Various techniques have been demonstrated to achieve multi-wavelength operation in EDFLs including cooling down EDF in liquid nitrogen, inducing FBGs with multi phase shifts in linear and ring cavity configurations. Recently, single-polarisation and dual-wavelength switchable fibre laser has been reported by using intracavity FBGs made in polarisation maintaining (PM) fibre, utilising polarisation hole-burning (PHB) effect to reduce homogeneous linewidth of the EDFL. In our work, we demonstrate a stable, single-polarisation and dual-wavelength switchable fibre laser by incorporating two special tilted fibre gratings (TFGs) into an EDF ring laser cavity: one with tilted structure at 45ºand used as an in-fibre polariser and the other at ~77º as a polarisation loss dependent filter. In such an EDFL system, the operation of dual-wavelength or wavelength switching is simply achieved by properly controlling the light polarisation status in the cavity.

2. **Fabrication and Characterisation of Gratings**

Three types of fibre grating have been used in the proposed laser system. The gratings were inscribed by scanning phase mask technique in standard single mode fibre (SMF-28) and B/Ge co-doped photosensitive fibre using a 244nm UV beam from a frequency doubled Ar^+ laser. The fibres were photosensitised by high pressure H_2-loading at 100º C for 2days prior to UV-inscription.

2.1 Seeding Fibre Bragg Gratings

We have fabricated two normal structure FBGs to serve as seeding wavelength resonators in our EDFL system with resonance wavelengths at 1547.05nm and 1551.67nm, matching the loss peaks of 77°-TFG. The reflectivities of these two FBGs were 2.51dB and 2.28dB respectively for the two wavelengths and their spectra are shown in fig. 1.



(a) (b)

Figure 1. Spectra of the two seeding FBGs with peak wavelengths at (a)1547.05nm;(b)1551.67nm

2.2 The property of the 45°-TFG

The 45° -TFG used in the EDFL system was from previous fabrication, which has the highest PDL around 1550nm region. It was fabricated using a short normal phase mask, so concatenation method was employed to create a ~50mm long 45°-TFG by concatenating 9 sub gratings. Fig. 2 gives the PDL profile of this 45° -TFG over a wavelength range from 1450nm to 1700nm. It can be seen that the polarisation extinction ration of this grating is about 35dB at ~1550nm.

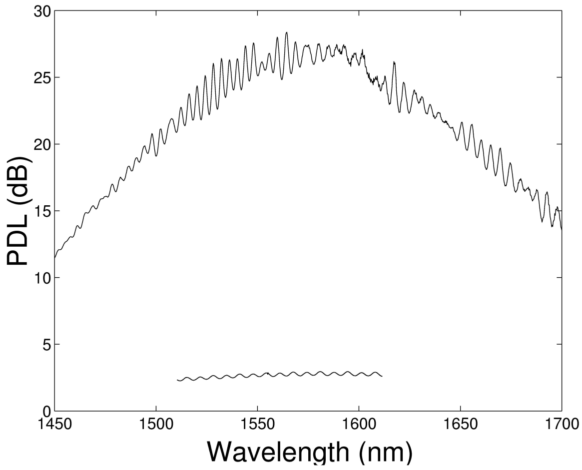


Figure 2. Measured PDL spectrum of the 45 °-TFBG used in the experiment.

2.3 The property of the 77°-TFG

The 77°-TFG was fabricated with a custom designed amplitude mask. According to our reported work, such a grating exhibits a series of loss bands with dual-peak feature over a few hundred nm region. These loss bands are generated by the coupling to the high order cladding modes satisfying phase match condition. By finely adjusting the tilt angle of the amplitude mask, the paired loss bands can fall into C-band of EDF. The spectra of one of the paired loss peaks of the fabricated 77°-TFG is shown in fig.3.

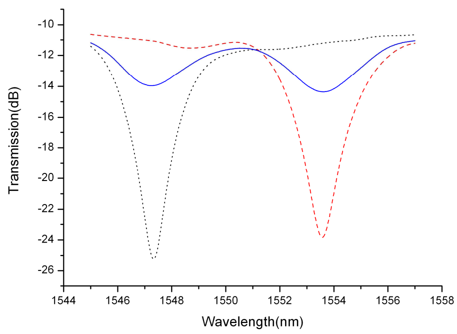


Figure 3. Transmission spectra of one paired polarisation peaks of 77 °-TFG measured with randomly (blue line) and fully polarised light (black dotted line - fast-axis peak; red dashed line – slow-axis peak).

It can be seen clearly from fig.3 that when the probe light is randomly polarised, the two peaks exhibit a near-equal loss of ~3dB, indicating the light is coupled more equally to the two modes with orthogonal polarisation states. When the probe light is fully polarised, one of the peaks will grow to its full strength (14dB loss at 1547.3nm for the fast-axis mode and 12.6dB loss at 1553.5nm for the slow-axis mode) while the other is almost eliminated. The bandwidths for the fast-axis and slow-axis loss peak are about 2.6nm and 2.8nm, respectively.

3 Experimental Setup of the Proposed Fibre Laser and Results

The set-up for proposed EDFL is shown in fig. 4. In this configuration, the gain medium is a 10m highly erbium doped fibre, which is pumped by a low power 975nm laser diode (only available in the lab) through a 980/1550 WDM coupler. Uni-direction oscillation of the fibre laser is ensured by the optical isolator (OIS). The laser output is coupled out by a 30:70 coupler. A polarisation controller (PC) is placed between the 77^o-TFG and 45^o-TFG. Two normal FBGs (G1 and G2) functioning as seeding wavelength resonators are coupled into the laser cavity via a circulator which also behaves as an isolator to ensure the single direction oscillation. The end of the FBG array is terminated by index matching gel in order to eliminate background ASE noise.

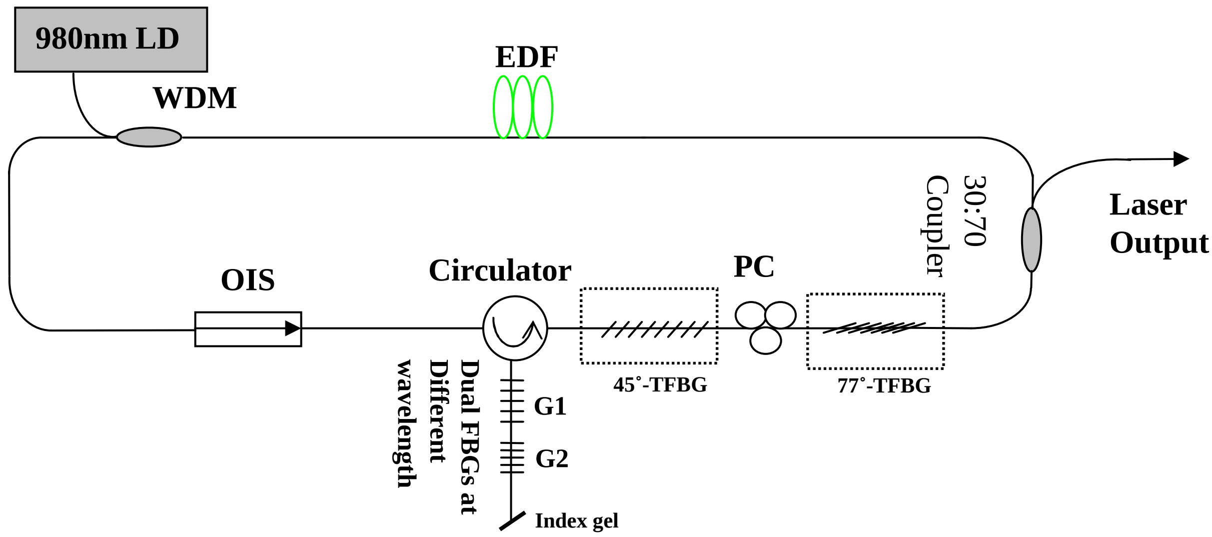
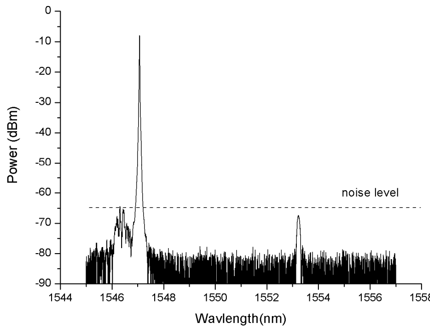


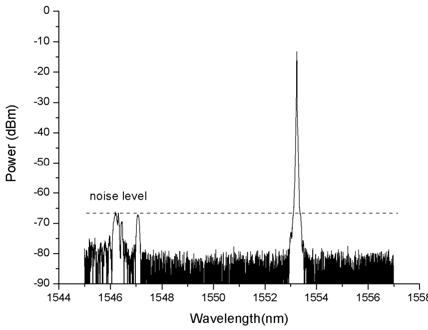
Figure 4. Schematic diagram of TFG based single-polarisation and wavelength switchable EDFL.

The operation principle of the fibre laser is described as follows. Since the 45^o-TFG is an in-fibre polariser, its presence in the fibre ring laser will force the cavity oscillate in single polarisation regime. The 77^o-TFG is a polarisation dependent loss filter which will induce some loss to the cavity around its paired attenuation band region, thus imposing PHB effect to the gain medium. The amplitude of the loss depends on the polarisation state of the light travelling in 77^o-TFG. By controlling the polarisation state of the light entering the 77^o-TFG using the PC, the laser cavity can give single-polarisation single-wavelength output at either 1547nm or 1553nm region or lasing at dual-wavelength mode with orthogonal polarisations.

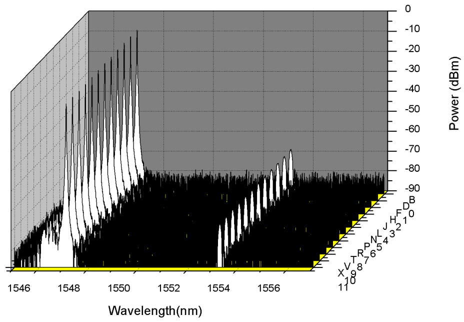
When the light launched to 77°-TFG is polarised in equivalent fast- or slow-axis direction of the 77°-TFG, the laser will give single-polarisation and single-wavelength output. Fig.5 (a) and (b) show the single wavelength oscillation of the fibre ring laser at the two seeding wavelengths of 1547.07nm and 1553.24nm, respectively. 12 scans at 5mins interval in one hour for both wavelengths are also shown in Fig.5 (c) and (d). The amplitude variation was measured to be less than 0.5dB within 1 hour at laboratory condition. From these results we can see that the optical signal to amplified spontaneous emission (ASE) ratio is more than 65dB for both laser lines and the optical signal to noise ratio (OSNR) for both laser lines is more than 50dB. Single polarisation operation was verified by connecting the output to a polarisation controller followed by a polariser. The measured degree of polarisation (DOP) was ~35dB for 1547.07nm and ~30dB for 1553.24nm laser lines, indicating high degree of single polarisation operation.



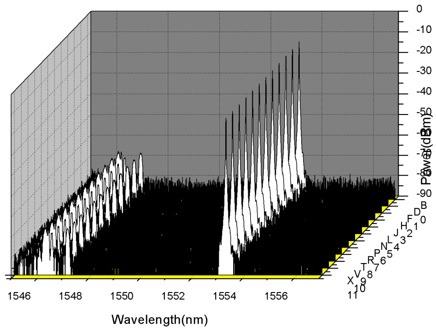
(a)



(b)



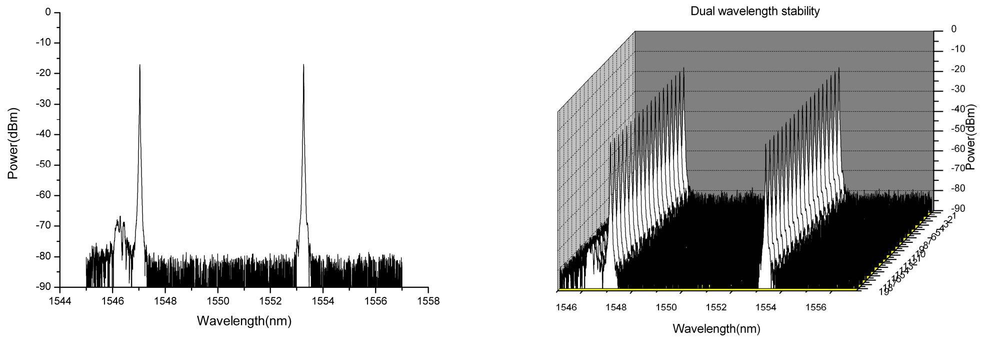
(c)



(d)

Figure 5. Stable single wavelength lasing oscillation of the proposed fibre ring laser at two seeding wavelengths (a) & (c) 1547.07nm and (b) & (d)1553.24nm.

If we change the polarisation direction of the light launching to 77°-TFG at 45 degree to the fast- and slow-axis of the TFG, we shall have dual-wavelength output of two orthogonal polarisations. Fig.6 (a) shows that the dual-wavelength output at ~1547.07nm and ~1553.24nm of the fibre ring laser. We have continuously monitored the dual-wavelength output for 20mins, and no noticeable amplitude variation was observed for a fixed position of the PC at room temperature. This is shown in Fig.6 (b). The signal to ASE ratios of both lasing lines were more than 60dB and the OSNRs were around 50dB and 63dB at 1547.07nm and 1553.24nm. The linewidths of both single- and dual- wavelength laser output were measure to be less than 0.01nm. The linewidth may be even narrower, since the measurement could be limited by the resolution of the optical spectrum analyser (ANDO 6317B).



(a) (b)

Figure6. (a) Dual wavelength operation of the proposed fibre laser, (b) stability experiment of dual wavelength oscillation

Although we only demonstrated single- and dual-wavelength operation at fixed wavelengths, because the reflection bands of the FBGs are much narrower than the paired loss peaks of 77°-TFG, the system has a capability of tuning operation within the range defined by the bandwidths of the loss peaks. In addition, switchable multi-wavelength (more than two) output may be realised by using several TFGs with un-overlapped spectra.

4 Conclusion

In summary, we have demonstrated a novel, stable, single-polarisation and dual-wavelength switchable fibre ring laser by using TFGs with tilted angles ≥45° as polariser and polarisation dependent loss filter. The TFGs were all made in single mode fibres, thus giving low splicing loss advantage. Both single-wavelength and dual-wavelength operation were achieved by simply adjusting the polarisation controller in the system. The measured optical signal to ASE ratio and the OSNR were as high as 65dB and 50dB and the lasing operation was very stable at laboratory condition.

Report 3B

Multi-Wavelength Switchable Fibre Ring Laser Based on Polarisation Selective Tilted Fibre Gratings Capable of Strain and Temperature Sensing

01/2009

Photonics Research Group
Aston University

Contents:

1. **Introduction**
2. **Fabrication and characterisation of fibre gratings used in the fibre ring laser system**
3. **Operation principle of the multi-wavelength switchable fibre ring laser**
4. **Characterisation of the fibre ring laser**
5. **Sensing capability of the ring laser cavity**
6. **Conclusion**
7. **Reference**

1. Introduction

Multi-wavelength fibre lasers are potentially useful sources for a range of different applications, such as wavelength division multiplexed (WDM) fibre communications, optical fibre sensing and instrumentation and system diagnostics [1], [2], [3] and [4]. However, due to low birefringence of standard telecom and Er-doped active fibres, the output of a fibre laser in general is not in single polarisation state. Numerous techniques have been developed to achieve a single polarisation operation for fibre lasers. Examples can be referred to integrating an integral polariser [5] and incorporation of a high birefringence rare-earth doped fibre with two anisotropic fibre Bragg gratings (FBGs) [6]. Although these techniques can provide a very high degree of single polarisation oscillation, they suffer from being difficult to fabricate and they may induce a high insertion loss to the laser cavity leading to low efficiency. The advantages of intrinsic fibre compatibility and low cost fabrication of FBGs in single mode fibres make them the ideal wavelength selective devices for fibre lasers. Many studies have been focused on the operation mechanism of multi-wavelength fibre lasers such as an Er-doped fibre (EDF) ring laser with two cavities [7], a coupled dual cavity fibre laser [8], and a fibre laser with twin-peak reflection grating [9]. In such laser systems, the EDF is the primary gain medium, however, because of the homogenous broadening nature of the EDF, it is difficult to obtain simultaneous or switchable wavelength oscillation in EDF laser. Furthermore, the homogenous gain broadening of the EDF will result in wavelength competition, even ceases the laser oscillation.

In the work we report here, we have employed three fibre gratings made in single mode fibre with excessively tilted structures – one is tilted at 45º (named as 45º-TFG) and the other two at 77 º (77 º-TFG) and at 81 º (81º-TFG) – as one in-fibre polariser and two polarisation loss dependent filters, respectively, to realise the single polarisation and multi-wavelength switchable operation for an EDF fibre ring cavity laser system. We have achieved single, double, triple and quadruple wavelength oscillation at room temperature condition. An optical signal to noise ratio higher than 50dBm has been obtained for all lasing wavelengths. In addition, because the bandwidths of the seeding FBGs (normal structure gratings), are narrower than the loss bands of the tilted gratings, the laser output signal has a certain tenability which can be utilised for optical sensing. We have performed the temperature and strain sensing experiment by subjecting one of the seeding FBGs under temperature and strain variation. High resolution temperature and strain sensing over a relatively large dynamic range has been demonstrated using this system.

2. Fabrication and characterisation of fibre gratings used in the fibre ring laser system

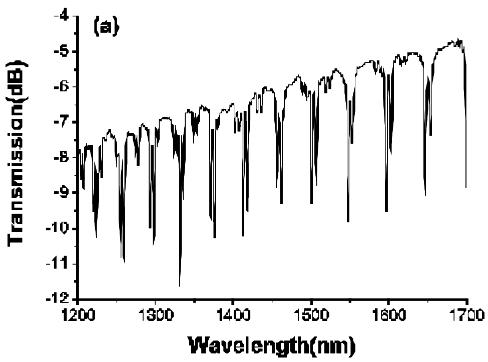
According to our group’s previous study [10], a specially designed 45 º-TFG exhibits an ideal in-fibre polariser functon as it can provide a strong polarisation dependent loss (PDL) ~ 30dB over nearly 80nm bandwidth in 1550nm region. The 45º-TFG used in our fibre ring laser system was UV-inscribed in the hydrogen loaded B/Ge single mode fibre using scanning phase mask technique. The period of the employed phase mask was 1800nm. To achieve the tilted fringes at 45º in the fibre core and induce the radiation response around 1550nm region, the phase mask was rotated at 33.7º respecting to the fibre axis in the UV-inscription. Limited by the size of the

phase mask, concatenation method was used in the fabrication to obtain a ~5cm long 45°-TFG. The PDL profile of this grating is very similar to the one shown in ref [10], giving 28dB polarisation extinction ratio from 1480nm to 1560nm.

The other two tilted gratings were fabricated in order to give strong polarisation dependent loss around the four designed seeding wavelengths. According to our design, two gratings with 77° and 81° tiled structures may be used as the polarisation dependent loss filters to match the wavelengths of the four seeding FBGs in 1550nm region. Thus, the 77°-TFG and 81°-TFG were UV-inscribed in hydrogen loaded standard telecom (SMF-28) fibre using a custom-design phase mask with a 6.6μm period. The mask was carefully rotated at 73° and 79° in the inscription system to obtain the designed tilted grating structures.

Figures 1(a) and 2(a) depict the transmission spectra of the 77°- and 81°-TFG measured in the wavelength region from 1200nm to 1700nm. From the figures we can see clearly that there is pronounced peak splitting feature on the spectra and all the peaks are relatively weak giving strengths around 2-3dB. These two spectra were measured using unpolarised light. When we inserted a polariser and a polarisation controller between the broadband source and the TFG, either split peak was excited depending on the polarisation of the probe light. As clearly shown in Figure 1(b) and 2(b), which give two zoomed split-peaks for 77°-TFG and 81°-TFG, respectively, we see that when the light switched from the fast-axis polarisation to the slow-axis one, the peaks at the shorter wavelength sides vanish while the peaks at the longer wavelength side grow to maximum and vice versa. This evidently indicates that the 77°-TFG and 81°-TFG are strong polarisation loss dependent filters and this property can be utilised to induce wavelength selective polarisation-hole-burning (PHB) effect to realise multi-wavelength switchable function in proposed fibre ring laser system.

In the proposed fibre ring laser system, four normal structure FBGs were used as seeding wavelengths and fed to the ring cavity via an optical circulator as shown in Figure 3. These four FBGs were fabricated in hydrogen loaded SMF-28 fibre using standard UV-inscription and phase mask technique. The Bragg wavelengths and reflectivities for the four FBGs were 1547nm/2.5dB, 1553nm/2.2dB, 1563nm/2.1dB and 1569nm/5.6dB, respectively. These four wavelengths were chosen to match the four polarisation loss bands of the 77°-TFG and 81°-TFG in 1550nm region. All tilted and normal structure gratings were thermally annealed at 80°C for 48 hours after the fabrication to stabilise their spectral property.



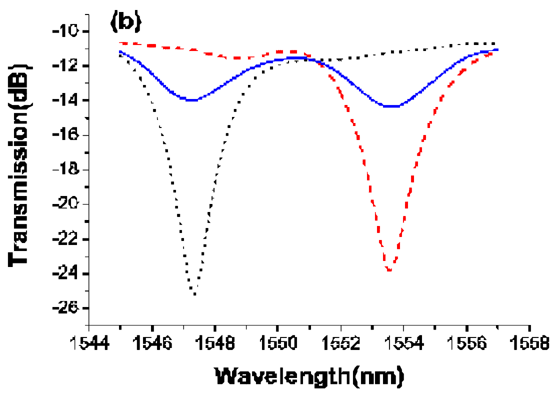


Figure.1. (a) Transmission spectrum of the 77°-TFG over wavelength range 1200nm – 1700nm; (b) Zoomed spectra of one paired polarisation loss peaks of 77 °-TFG around 1550 nm measured with randomly (solid line) and fully polarised input lights (dashed lines).

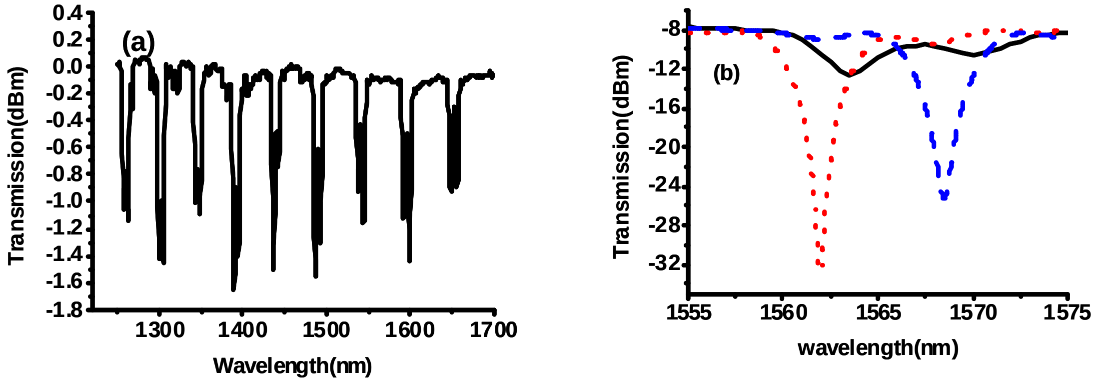


Figure.2. (a) Transmission spectrum of the 81 °-TFG over wavelength range 1200nm – 1700nm; (b) Zoomed spectra of one paired polarisation loss peaks of 81 °-TFG around 1550 nm measured with randomly (solid line) and fully polarised input lights (dashed lines).

3. Operation principle of the multi-wavelength switchable fibre ring laser

Figure.3 shows the set-up of the proposed multi-wavelength switchable fibre ring laser system. In this configuration, the gain medium is a 10m of highly erbium doped fibre, which is pumped by a 975nm laser diode through a 980/1550 WDM coupler. An optical isolator (OIS) ensures an anticlockwise ring cavity. The 30% arm of the coupler is used as the output port of the laser. The 77º-TFG and 81º-TFG behave as the polarisation dependent spectral loss filters and the 45º- TFG is used as an in-fibre polariser in the system to ensure the laser operating in a single polarisation state and wavelength switchable regime.

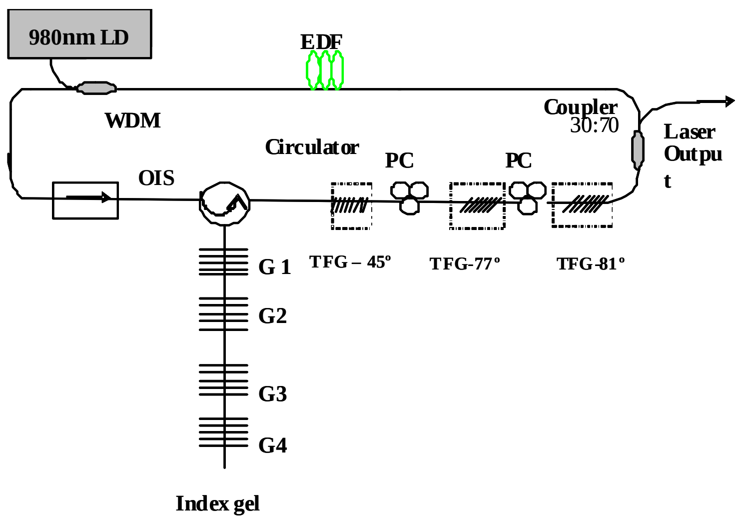


Figure.3. Schematic diagram of the experimental setup for the multi-wavelength switchable fibre ring laser.

Two fibre polarisation controllers (PCs), one placed between 45º-TFG and 77º-TFG and the other placed between 77º-TFG and 81º-TFG, are employed in the system to adjust the polarisation state of the cavity. The four standard FBGs (G1, G2, G3 and G4), whose wavelengths are matched with the loss bands of the TFG polarisation loss filters, are functioning as seeding wavelength selectors and coupled into the laser cavity via a circulator. This circulator also acts as an isolator to maintain the single direction oscillation. Since the reflection bands of the four seeding FBGs are narrower than the loss bands of the TFGs, the four FBGs can be used as temperature and strain sensors to give the system sensing capability. The end of the FBG array is terminated by index matching gel in order to eliminate background ASE noise. By introducing PDL, cavity loss can be controlled and wavelength of laser line can be varied. Therefore it is possible to operate the laser giving output at single, double, triple and quadruple wavelength operation by simply adjusting the polarisation state of the light entering the 77º-TFG and 81º-TFG using the PCs. As FBGs are sensitive to the temperature and strain changes the laser wavelength can be tuned continuously by heating and stretching or compressing the FBGs within the range defined by the TFG loss band.

4. Characterisation of the fibre ring laser

By adjusting the PCs to control the polarisation state of the light entering the 77º-TFG and 81º-TFG (polarised in the equivalent fast- or slow-axis of the TFGs), single-wavelength lasing at either the four seeding wavelengths has been demonstrated. Figures 4 (a) - (d) evidently show the single wavelength oscillation of the fibre ring laser at the four seeding wavelengths at 1547.05 nm, 1553.27 nm, 1563.05 nm and 1568.97 nm., respectively. We have also measured the pumping efficiency for the EDF system just for lasing at ~1553nm. For this experiment, the output of the ring cavity was connected to an optical spectrum analyser (OSA) first and we then increased the driven current to the 975nm pump diode. When the current was below the threshold, we only saw ASE broad spectrum on the OSA and, as soon as the current reached the threshold, we saw a narrow lasing peak at ~1553nm occurred on the OSA. At this point, the output terminal of the ring laser was disconnected from the OSA and attached to a power meter via a pigtail fibre. We then recorded the output power of the laser for each driving current. Figure 5 plots the laser output against pumping current for the lasing wavelength at ~1553nm. From the figure we can estimate that the apparent pumping efficiency is about 1.95µW/mA.

We also verified the single polarisation state of the outputs for this fibre ring laser system by connecting the laser output to a polarisation controller followed by a commercial polariser and a power-meter. The measured degree of polarisation (DOP) was in the range of 30dB (99.80%) to 35dB (99.94%) for the lasing oscillation at four different wavelengths, indicating a very high degree of single polarisation operation of the laser system.

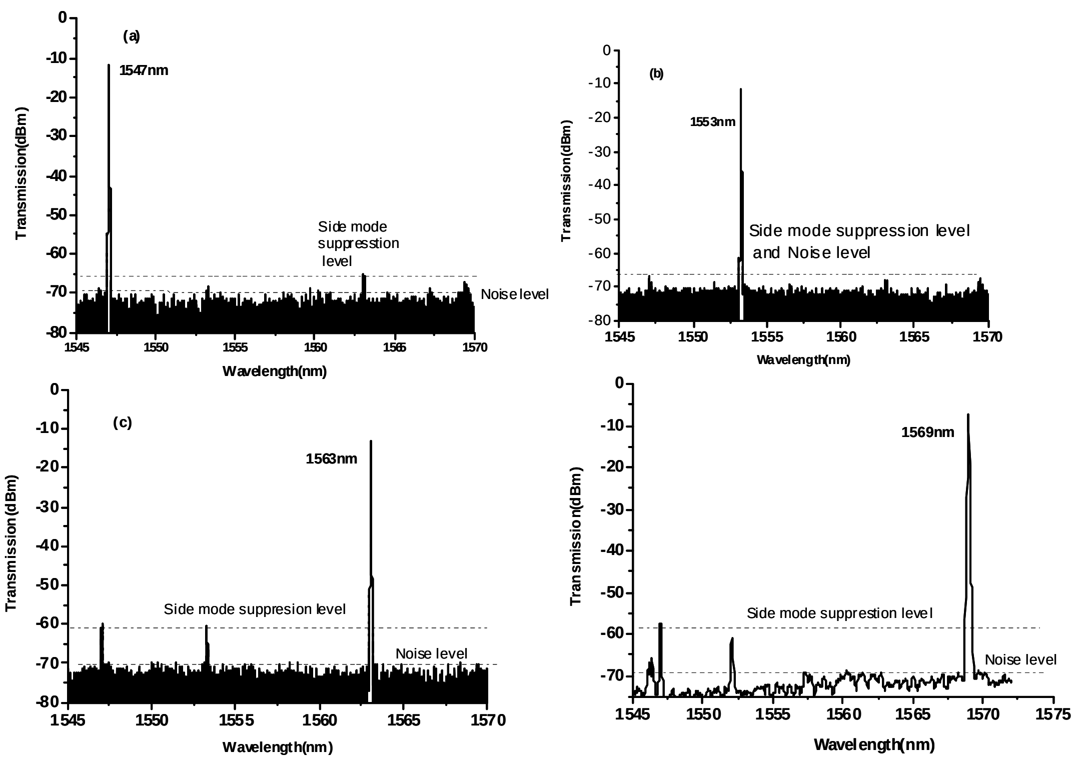


Figure. 4 Single wavelength lasing at (a) 1547.05 nm, (b) 1553.27 nm, (c) 1563.05 nm and (d) 1568.97 nm.

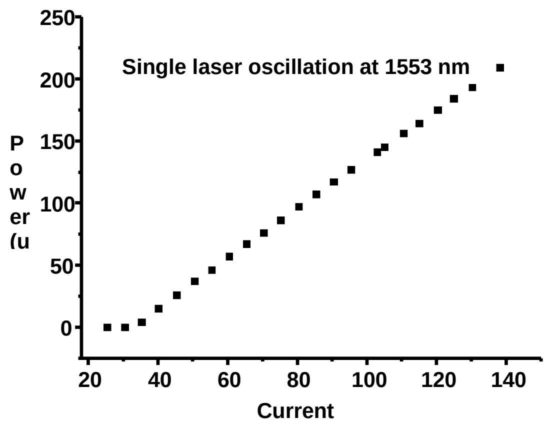


Figure.5 Output power vs pump diode current for lasing at 1553nm

Similarly, by adjusting the two PCs to change the polarisation state of the light entering the 77º-TFG and 81º-TFG as this will change the PHB profile, the laser oscillation at double, triple and quadruple wavelengths can be achieved in this system. Figure 6 (a), (b) and (c) show three sets of dual-wavelength oscillations at 1547.06nm/1553.27nm, 1547.06nm/1563.07nm and 1547.06nm/1563.07nm, respectively. Figure 7 (a) and (b) show the two sets of spectra for triple-wavelength oscillations at 1546.94nm/1551.99nm/1562.63nm and